

# Autonomous Formation Flying of Micro Aerial Vehicles for Communication Relay Chains

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## BIOGRAPHIES

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## KEYWORDS

autonomous micro aerial vehicle, formation flying, communication relay chain, emergency communications

## ABSTRACT

In this paper we describe the use of GNSS location determination for formation flying of multiple Micro Aerial Vehicles (MAVs). These MAVs are the core component of a system that realizes a chain of airborne communication relays to provide communication services

to mobile terminals. This chain of communication relay nodes improves wireless radio communication by utilizing two effects. Firstly, a chain of relay nodes is able to convert an unfavorable non-line-of-sight condition to a line-of-sight condition by positioning its nodes around the obstacle. Secondly, relay nodes reduce free-space losses. The transmission of a radio signal in free-space is subject to a reduction in received signal power proportional to the square of the distance between transmitter and receiver. By placing a communication relay between the original transmitter and receiver, the distance is cut in half, reducing the required transmission power for each transmitter by a factor of four. The reductions in required transmission power can be directly utilized to increase the range and/or data rate of the communication system. The motors required to hover the relay platform also consume power, typically more than the transmission power. But as the transmission power of a single antenna is limited and cannot be increased over a certain level, range and bandwidth are limited. Flying relay nodes increase the necessary total electrical power, but offer the possibility to enhance range and data rate above the limits of a single node. Location determination of all involved network nodes, both airborne and on the ground, is crucial for determining and maintaining the optimal formation as well as network routing information. Due to the known spatial configuration of the nodes, routing is significantly simplified, since the network topology neighborhood relations are known. Routing tables can be initialized and maintained based on the knowledge of the nodes' spatial configuration. We provide experimental results carried out with up to six nodes. Four of which are autonomous quadrotor MAVs, which are able to hover at a fixed position. One ground terminal acts as a stationary base, another ground terminal is mobile and moves. The optimal formation, given the positions of the ground stations, is automatically determined and maintained by the fleet of quadrotor MAVs. We discuss a suite of necessary further work, including automatic replacement, rearrangement and replenishment of MAVs, as well as covering user terminals at multiple locations and perching of MAVs in order to extend their battery life.

## INTRODUCTION

Communication capacity is a crucial asset for many tasks in applications such as disaster management operations, defense, exploration, or polling sensors and sensor networks. Unfortunately, difficult on-site radio propagation conditions often impair communications. In order to provide communication capacity in difficult and unpredictable propagation conditions, GNSS location determination can be used for formation flying of multiple Micro Aerial Vehicles (MAVs). These MAVs are the core component of a system that realizes a chain of airborne communication relays to provide communication services to mobile terminals. This chain of communication relay nodes improves wireless radio communication by utilizing two effects:

Firstly, a chain of relay nodes is able to convert an unfavorable non-line-of-sight condition to a line-of-sight condition by positioning its nodes around the obstacle.

Secondly, relay nodes reduce free-space losses. The transmission of a radio signal in free-space is subject to a reduction in received signal power proportional to the square of the distance between transmitter and receiver. The regulatory restricted maximal transmission power of an antenna limits the performance of the radio link, in terms of range and data rate. By placing a communication relay between the original transmitter and receiver, the distance is cut in half, reducing the required transmission power for each transmitter by a factor of four. The reductions in required transmission power can be directly utilized to increase the range and/or data rate of the communication system. The hovering of the relay platform also consumes power, typically more than the transmission power. But as the transmission power of a single antenna is limited and cannot be increased over a certain level, range and bandwidth are limited. Flying relay nodes increase the necessary total power, but offer the possibility to enhance range and data rate above the limits of a single node.

Location determination of all involved network nodes, both airborne and on the ground, is crucial for determining and maintaining the optimal formation as well as network routing information. We argue that GNSS-based location determination is well-suited to fulfill the necessary requirements in terms of accuracy and availability, due to the correlation of large portions of the error budget (tropospheric, ionospheric) for all involved nodes in the application areas of such communication relay chains. These application areas are both military and civilian, such as disaster management operations, including situation assessment or urban search and rescue.

The chain of relays is an instance of a wireless ad hoc network, where each node forwards packets to its neighboring nodes. Due to the known spatial configuration of the nodes, routing is significantly

simplified, since the network topology neighborhood relations are known. Routing tables can be initialized and maintained based on the knowledge of the nodes' spatial configuration.



Figure 1 Hummingbird AutoPilot

The paper is organized as follows:

We will briefly discuss our concept and the rationale behind utilizing aerial relay nodes. After that, we provide experimental results carried out with up to six nodes. We will further discuss a suite of necessary further work, including automatic replacement, rearrangement and replenishment of MAVs and perching of MAVs in order to extend their battery life.

## CONCEPT OF COMMUNICATION RELAY CHAIN

Our concept is based on the following two assumptions:

- 1.) In free-space conditions, the transmission power required by wireless radio communication grows with the square of the distance between transmitter and receiver.
- 2.) Non-line-of-sight conditions impair the radio channel by blocking and multipath, both resulting in signal fading.

If we are able to partition the long distance between communication partners into multiple shorter and concatenated segments, we are able to convert non-line-of-sight situation to multiple line-of-sight segments with significantly better conditions for radio propagation.

To define suitable positions for the relay nodes, we consider  $N$  Micro Aerial Vehicles hovering in  $\mathbb{R}^3$ . We denote the state of the  $i$ -th vehicle by  $\vec{x}_i$ , where  $i \in \{1..N\}$  and  $\vec{x}_i$  is the vehicle's position in  $\mathbb{R}^3$ .

We denote the state of the two end points, base and mobile, by  $\vec{x}_b$  and  $\vec{x}_m$ , respectively. Assuming flat terrain and a minimum height  $h_{\min}$  above ground, the desired position  $\vec{x}_i^*$  of the  $i$ -th vehicle is only a function of  $\vec{x}_b$ ,  $\vec{x}_m$ ,  $i$ ,  $N$  and  $h_{\min}$ .

$$\vec{x}_i^* = (\vec{x}_m - \vec{x}_b) \cdot \frac{i}{N+1} + h_{\min} \cdot \vec{e}_z \quad (1)$$

The necessary transmission power  $P_{TX,0}$  to achieve a required signal-to-noise ratio (SNR) at a receiver in free-space is proportional to the square of the distance  $d$  between transmitter and receiver.

$$P_{TX,0} \propto d^2 \quad (2)$$

By putting  $N$  equally spaced relays between the transmitter and the receiver, the path between transmitter and receiver is split into  $N+1$  segments, each of length  $d/(N+1)$ .

Hence, the required power for each of the  $N+1$  transmitters is

$$P_{TX,N} = P_{TX,0} \cdot \frac{\left(\frac{d}{N+1}\right)^2}{d^2} = P_{TX,0} \cdot \frac{1}{(N+1)^2} \quad (3)$$

It is obvious that any deviation from this assumption of linearly aligned and equally spaced relays will increase the required power for at least one transmitter. Hence, the performance of the communication system depends on exact station keeping which in turn is influenced by the accuracy of the location determination.

Only minimal routing information needs to be exchanged. The direct geometric neighbors need to be known and configured as gateways (the location information fully determines the routing configuration).

## EXPERIMENTAL SETUP

We conducted our experiments on an outdoor sports area in Wessling, Germany (48.0695°N, 11.2406°E). It provided enough space without obstacles and good GPS signal reception.

We employed common-off-the-shelf quadrotor based Micro Aerial Vehicles and equipped them with an additional embedded CPU (ARM Cortex-A8 with 720 MHz, 256MB RAM and 256MB Flash) and a radio communication module operating at 2.4 GHz (IEEE 802.11 b/g), which is shown in Figure 2. The embedded CPU was operated under an embedded Linux distribution (Angström). Additionally, two laptops running Linux (Ubuntu) were configured as “Base” (192.168.12.100) and “Mobile” (192.168.12.200).

The four aerial nodes were configured as relay nodes (starting with 192.168.12.101 up to ...104). We deliberately set the routing configuration to only allow forwarding to the next neighbour of each node. The resulting multihop relaying was verified by *traceroute*.

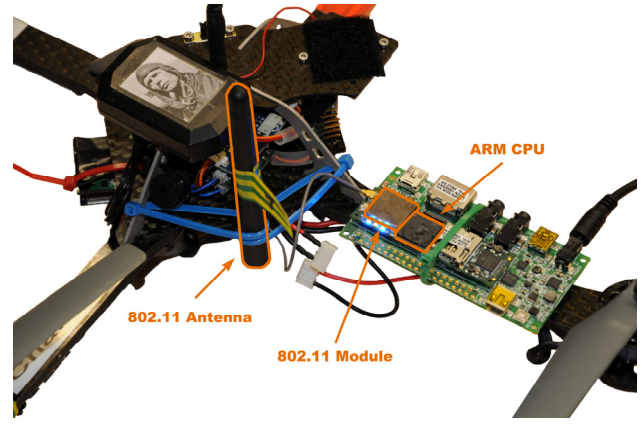


Figure 2 Micro Aerial Vehicle with additional embedded CPU, 802.11 radio module and antenna

The communication relay chain was formed by four quadrotors as mobile relay nodes and two laptops as end points (see Figure 3). One of the end points was positioned at a fixed location, the other one was mobile.

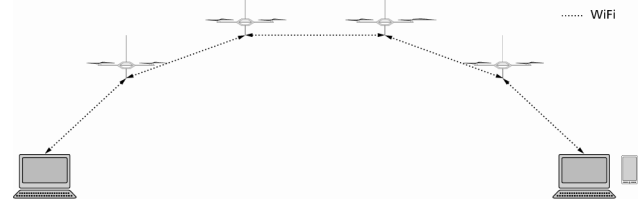


Figure 3 Lab test setup and concept of the flying communication relay chain

During the experiments, we used four quadrotors of the same type. For an easy identification we named them *Charles*, *Wilbur*, *Louis* and *Otto*. Each quadrotor was equipped with an IEEE 802.15.4 ZigBee module to be able to receive control commands. These control commands were sent by a central command server, who itself received commands from the Smartphone on the mobile chain end. Smartphone and control server have been connected using WiFi (see Figure 4).

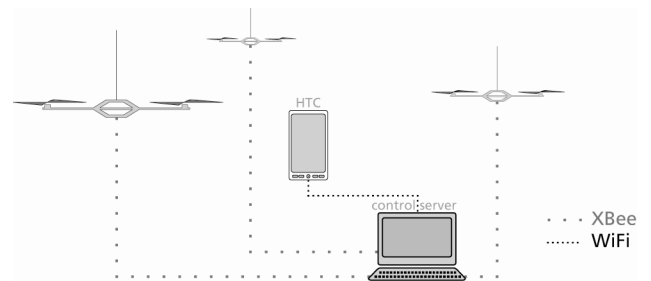


Figure 4 Experimental Setup - Network

In the outdoor experiment, the mobile node was realized by combining the laptop for data transfer over the relay chain, and a HTC Desire Smartphone (see Figure 5), which was used as position sensor and provided the formation control. This Smartphone is equipped with a GPS sensor and an IEEE 802.11 WiFi interface. The position for every quadrotor was calculated on the Smartphone, based on its own position and the fixed position of the opposite chain end. All positions were then sent to the control server, where they were encoded into waypoint commands and sent to the corresponding quadrotors.



Figure 5 Smartphone with GPS sensor and IEEE 802.11 WiFi

The control server had the additional functionality to provide a real-time overview (see Figure 6) of the measured positions (grey icons) and desired positions (orange icons) based on the NASA World Wind globe visualization software [9]. This software tool was not only used in the field, but also for visualization of our lab simulations.

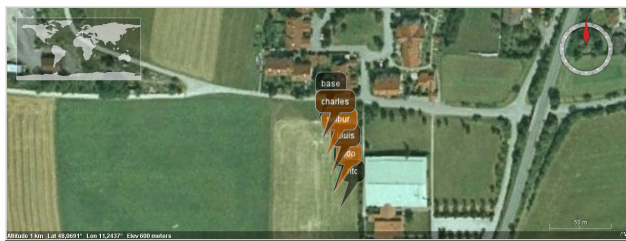


Figure 6 Screenshot World Wind on control server

## EXPERIMENTAL RESULTS

In experiment the mobile end of the communication relay chain was carried by a person repeatedly along a predefined path (see Figure 7), and the chain formation followed the movement.

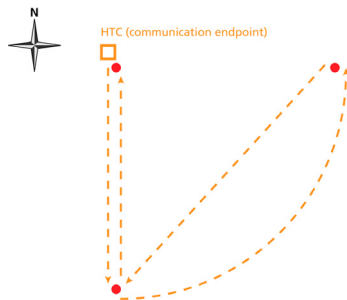


Figure 7 Predefined path of the mobile relay chain end

A picture of the setup and the alignment of four quadrotors is shown in Figure 8.

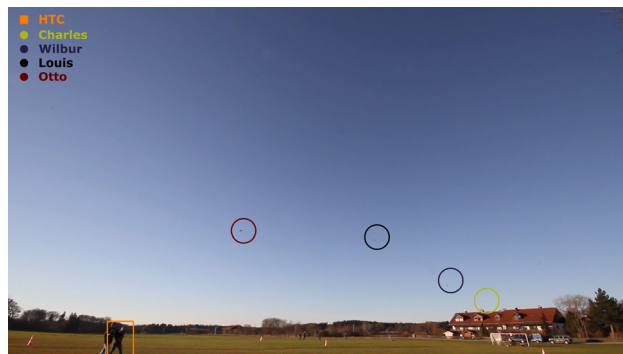


Figure 8 Relay chain during the experiment

We conducted this experiment several times. One of the runs is analyzed in more detail. The recorded tracks and the desired positions for every quadrotor captured during that run are shown in Figure 9. The orange track is formed by recorded GPS positions of the mobile relay chain end, i.e. the Smartphone. The four quadrotors are arranged in a chain facing towards the stationary end point. From mobile to fixed end, or from south to north in Figure 9, these were *Otto* at the mobile end, followed by *Louis*, *Wilbur* and *Charles*.

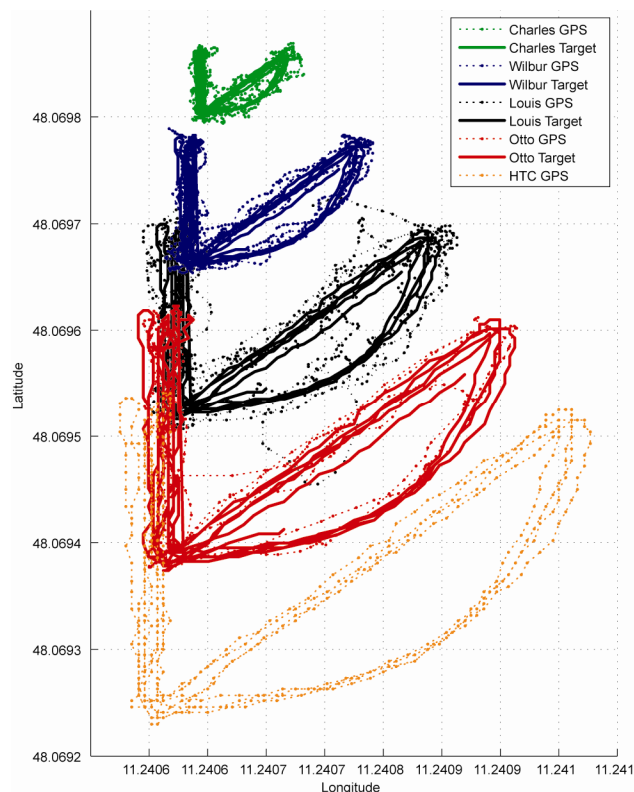


Figure 9 Tracks of the relay chain nodes

A more detailed view on the track of quadrotor *Otto* is provided in Figures 10 and 11. Figure 10 shows the



isolated track of *Otto*, flying in the fourth position, the southernmost place in the formation.

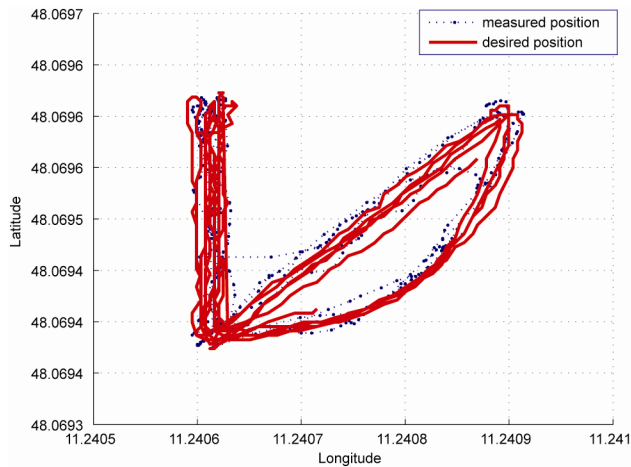


Figure 10 Otto measured and desired position

Figure 11 shows the measured position and the desired position over time, separated into latitude and longitude. As can be easily seen, there is a delay between target position input and measured GPS position of several seconds. The main cause of the delay between target and actual quadrotor positions is the inertia of the quadrotor system, further increased by the control parameters of the waypoint navigation which do not fully exploit the dynamic capabilities of the quadrotor.

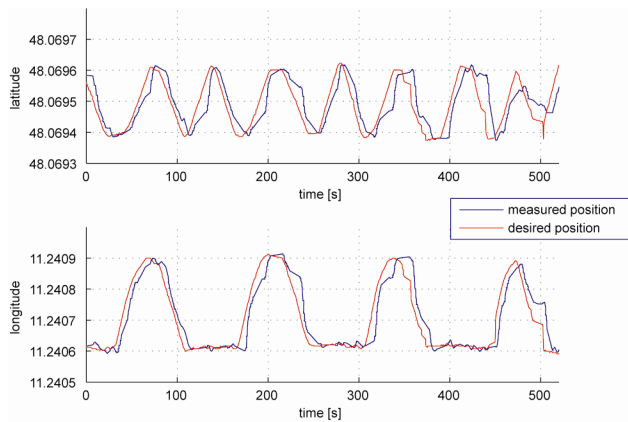


Figure 11 Otto position over time

One of the quadrotors (*Louis*) showed an interesting behaviour. As can be seen in Figure 12, *Louis* did not always follow a straight path towards a desired position, but mostly moved along an arc towards the next position.

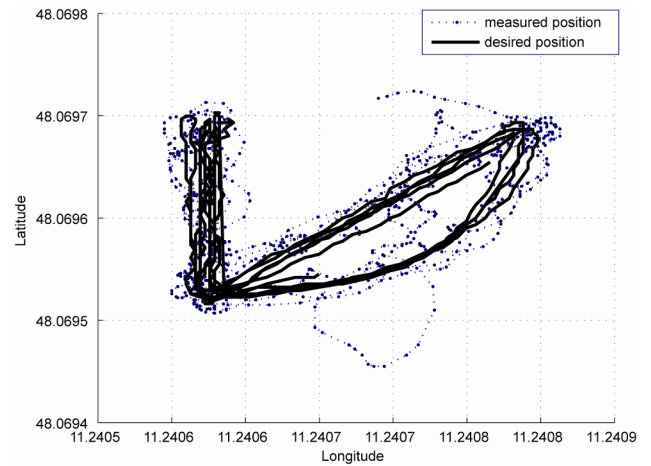


Figure 12 Louis measured and desired position

This behaviour can also be seen in Figure 13 which shows the position over time. The measured position is constantly oscillating around the target position with small amplitude, however the maximum error is smaller compared to the track of *Otto*.

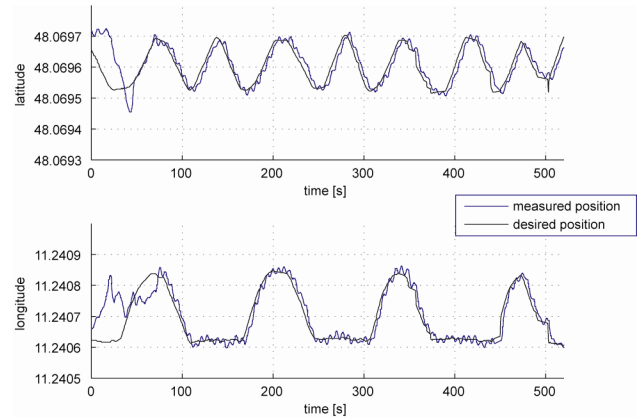
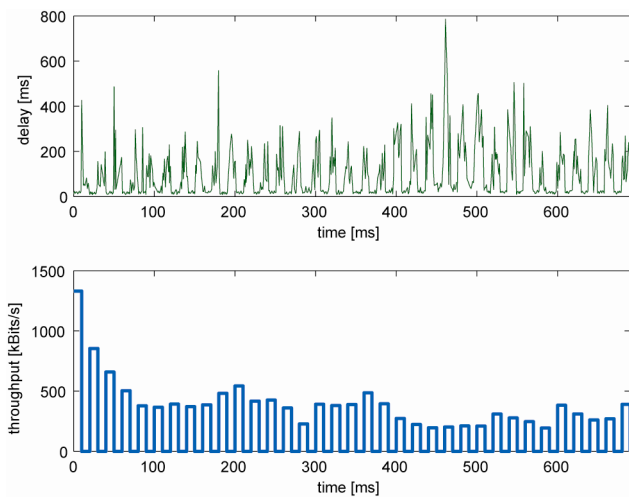


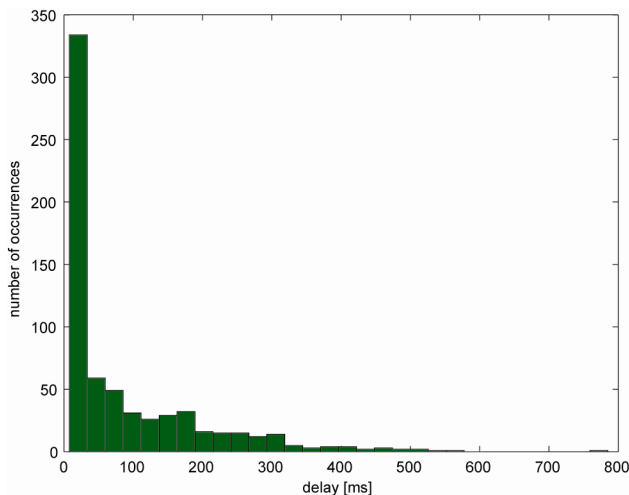
Figure 13 Louis position over time

In order to evaluate the communication performance, we measured throughput and delay of the relay chain. The result of the measurement can be seen in Figure 14, where delay and throughput are plotted over time. As we conducted throughput measurements at the same time, the delay is varying very much. For the throughput measurements we used *iperf*, a tool available for Linux systems. An *iperf* instance has to be started on both ends of the link to be tested. During the measurements, data packets are sent via the link for ten seconds and the mean throughput for this period is calculated. After a break of another ten seconds the process is restarted. This measurement process has been repeated during the whole runtime of the experiment, as can be seen in Figure 14.



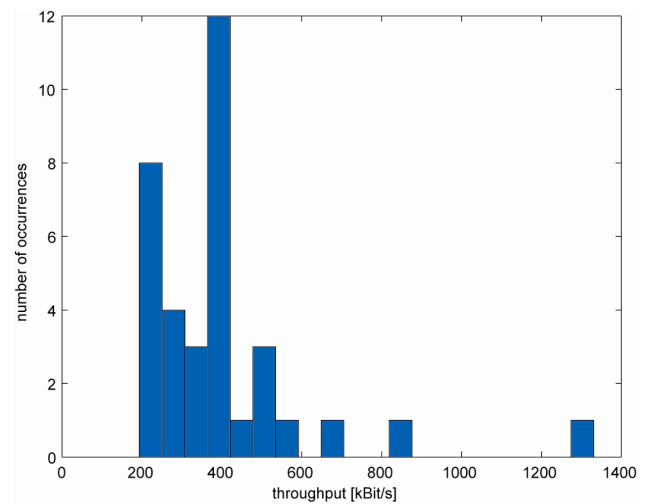
**Figure 14 Delay and throughput over time**

A histogram of the delay times can be shown in Figure 15. A total number of 660 delay measurements have been taken during the experiment, with a constant repetition rate of 1Hz. The maximum delay was 785 ms, the minimum around 8 ms.



**Figure 15 Histogram of delay measurements**

The histogram for the throughput result is shown in Figure 16. It can be seen that during the 35 measurements the throughput varied mainly between 200 and 600 kBit/s.



**Figure 16 Histogram of throughput measurements**

No communication dropout has occurred throughout the entire flight of the formation. The measured delay and throughput are sufficient for up to 20 permanent voice channels (more if inactivity is exploited) or even moderate resolution video communication.

## CONCLUSIONS AND OUTLOOK

We have achieved adaptive forming and maintaining of a communication relay chain formation consisting of four Micro Aerial Vehicles. Based on this stable formation we further achieved a stable performance of the communication. Our measurements have shown that the resulting delay and throughput are sufficient for voice and moderate resolution video communication. These results were achieved without any tuning of communication parameters to the specific scenario. Tuning of networking parameters to the specific conditions should yield further improvements. So far, we have not analyzed the correlation between positioning accuracy and communication performance. Since in our experiments the distance between the nodes has not been very large, the influence of the positioning accuracy on the performance may not be significant. Future experiments to systematically study this influence may require communication relay chains stretching over several hundreds of meters.

Low-cost common-off-the-shelf GPS receivers in combination with the MEMS-based IMUs have been sufficient to maintain the formation of the nodes. However, the GPS receivers appear to be susceptible to onboard radio interference, sometimes resulting in an elongated time-to-fix. We also observed oscillations in positioning accuracy on some occasions, which prompted us to maintain a slight vertical separation of the MAVs for safety reasons.

The payload capacity in terms of weight, volume, and electrical power is generally sufficient. However, the

additional weight and drag of the CPU-boards reduces the endurance of the MAVs to approximately 12 minutes.

In order to achieve persistent operation of the communication relay chain over the duration of many hours, the formation controller needs to automatically replace quadrotors that need recharging. Various forms of how the chain is reorganized to facilitate replenishments need to be compared in terms of their efficiency and operational feasibility.

Only a small portion of the power is necessary for operating the embedded CPU and the radio communication. Hence, a very challenging but promising approach to extend the operational time between charging of a quadrotor is perching on the ground or protruding structures, such as light poles, which would allow switching off the motors and navigation system.

While we currently employ a centralized formation controller implemented on an additional PC we intend to eliminate this component and realize a distributed control scheme on the quadrotors in order to increase the system's robustness.

Our experiments have shown the feasibility of a communication relay chain over a flat terrain. More challenging will be the operation of a relay chain that needs to follow a mobile inside of complex 3D environments, such as urban canyons, buildings or forests. In order to achieve this goal we need to extend our current system with the ability to simultaneously localize and map (SLAM) within such environments to achieve awareness of obstacles, both for deciding upon good positions in terms of radio propagation conditions and to avoid collisions with the environment as well as to realize safe perching.

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